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OPTIMAL COORDINATION OF POLICY INSTRUMENTS FOR A METROPOLIS WITH DECREASING POPULATION BASED ON URBAN MICROSIMULATIONS

NORIKO OTANI, FACULTY OF INFORMATICS, TOKYO CITY UNIVERSITY, OTANI@TCU.AC.JP
NAO SUGIKI, TRANSPORTATION DEPARTMENT, NS1491@DOCON.JP
KAZUAKI MIYAMOTO, FACULTY OF URBAN LIFE STUDIES, TOKYO CITY UNIVERSITY, MIYAMOTO@TCU.AC.JP
VARAMETH VICHIENSAN, FACULTY OF ENGINEERING, KASETSART UNIVERSITY, FENGVMV@KU.AC.TH

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Noriko Otani, Faculty of Informatics, Tokyo City University, 3-3-1 Ushikubo-nishi, Tsuzuki, Yokohama 224-8551, Japan, otani@tcu.ac.jp

Nao Sugiki, Transportation Department, Docon Co., Ltd., 4-1, 5-chome, 1-jo, Atsubetsuchuo, Atsubetsu, Sapporo 004-8585, Japan, ns1491@docon.jp

Kazuaki Miyamoto, Faculty of Urban Life Studies, Tokyo City University, 8-9-1 Todoroki, Setagaya, Tokyo 158-8586, Japan, miyamoto@tcu.ac.jp

Varameth Vichiensan, Faculty of Engineering, Kasetsart University, 50 Phaholyothin Rd., Jatujak, Bangkok 10900, Thailand, fengvmv@ku.ac.th

ABSTRACT

In population-decreasing metropolises, it is essential to coordinate a set of policy instruments with the conditions that the public expenditure is sustainable and that the level of public services is acceptable. The purpose of this study is to develop a method to coordinate a set of policy instruments rationally with the new concept of “public service demand management (PSDM)” based on urban microsimulations. The method is applied to a simple hypothetical city. The main concept behind the method is to identify a set of policy instruments that have the least costs from among possible alternative sets with future forecast through urban microsimulations, under the condition that the level of public services is maintained above a certain acceptable level. Since the number of possible alternative sets results in a combinatorial explosion problem, the harmony search algorithm is employed to identify an optimal set. The validity of the method is confirmed by applying it to the hypothetical city. After conducting several applications, it is found that the method proposes new sets of policy instruments that are not usually considered in the process of decision-making using the traditional ad hoc approach.

Keywords: ageing metropolises, policy instruments, public service demand management, urban microsimulations, harmony search

1. INTRODUCTION

A decrease in population is imminent in many industrialized metropolises. In addition, the financial condition of local governments in such metropolises is usually very serious; thus, it is necessary to control public expenditure. The cost of public services is strongly dependent on transport, land use, and the interaction between transport and land use. Therefore, in such metropolises, it is essential to coordinate a set of policy instruments with the conditions that the public expenditure is sustainable and that the level of public services is acceptable. The type of public services that citizens require depends on characteristics such as age and household type. Consequently, microsimulations based on individual households are necessary in order to estimate such demand for public services in the future. Bearing in mind the abovementioned situation, the purpose of this study is to develop a method to coordinate policy instruments rationally using the new concept of "public service demand management (PSDM)" based on urban microsimulations.

The method is applied to a simple hypothetical city. The main idea behind the method is to identify a set of policy instruments that have the least costs from among possible alternative sets with future forecast by urban microsimulations, under the condition that the level of public services is maintained above a certain acceptable level. It is a rather naive approach, if the cost of all alternative sets can be compared in a feasible period. However, it is not possible to calculate all the costs as the number of possible alternative sets results in a combinatorial explosion problem. In this study, the harmony search algorithm is employed in order to ascertain an optimal set. Harmony search is a music-based metaheuristic optimization algorithm that imitates the musical improvisational process (Geem *et al.*, 2001).

The validity of the method is confirmed by applying it to a hypothetical city. After conducting several applications, it is found that the method proposes new sets of policy instruments that are not usually considered in the process of decision-making using the traditional ad hoc approach.

2. APPROACHES FOR SELECTING POLICY INSTRUMENTS

Traditional transportation planning is often based on a transport demand model, which requires inputs of land use that have been forecast exogenously. In a larger context, it is incorporated in urban planning. However, because of the strong interaction between land use and transport, there are several applications of operational urban models that integrate land use and transport elements into the urban system. Basically, land-use models predict the future spatial distribution of households and employment in a particular study area. Several reviews have been conducted to compare and evaluate land-use models such as Wegener (2004) and Hunt *et al.* (2005). In the United States, due to significant environmental, traffic, and other impacts of land development, federal regulations guiding both environmental and transportation planning require modeling of travel and emissions on the basis of consistent assumptions regarding future land-use patterns. This encourages the development and application of a variety of land-use and travel-demand models, beginning from DRAM/EMPAL, and recently UrbanSim and PECAS. In Europe, applications of MEPLAN, TRANUS, and DELTA land-use models can be found in many cities and/or regions. In Japan, RURBAN has been continuously developed. In Latin America, there are numerous applications of TRANUS and MUSSA. These operational urban models may be classified into two groups: aggregated models and microsimulation models. Although the former type is intrinsically less complicated and for general application, the ranges of policy to be tested may be limited. The latter type is normally developed on the basis of individual behavior, mostly being for persons, households, business firms, and developers; thus, it represents the sophisticated real world more reasonably. Land-use policy instruments to be analyzed by land-use models include pricing, taxation, subsidy, housing and public service provision, land use regulation or zoning, etc.

Typical applications of land-use models usually address two problems: how land-use regulations or housing programs would affect land development and transportation, and how transportation improvements would affect the distribution of activities in an urban area. These models may be used as a tool in forecasting the future, envisioning policy, developing scenario planning, and evaluating policy options. Some land-use models are used in the policy-envisioning process, which is conducted as a cooperative process among people involved, such as business owners, community residents, interest groups, and local officials. On the other hand, some models are used in forecasting the future on the basis of the historical trends of development (Lemp *et al.* 2008). For example, UrbanSim (Waddell, 2011) has been employed to prepare land-use forecasts for Puget Sound Regional Council in Washington and is available for public review as part of its 2040 long-range transportation plan (PSRC, 2007); UrbanSim is also preparing 2030 land-use forecast for Austin, Texas (Kakaraparthi & Kockelman, 2011). In Atlanta, DRAM/EMPAL developed a 2040 land-use forecast; a new model is being developed on the basis of PECAS. Similarly, MENTOR, a customized version of MEPLAN, has been used in forecasting the future of Cambridge under several policy options, including congestion charging, public transport, walking, and cycling (Echenique, 2000). These policies are evaluated with respect to three dimensions of sustainability: economic efficiency, social equity, and environmental quality. Several indicators may be defined in this regard: transportation system efficiency such as vehicle kilometer travel (VKT) or VHT (vehicle hour travel), emission of air pollutants, energy consumption, economic efficiency such as cost of living, production cost, welfare change, equity and safety, etc. In this regard, the multiple criteria decision-making (MCDM) methods are required for multi-dimensional sustainability evaluation. Weighting of these indicators forms an easy-to-interpret index value. In Atlanta's Regional Transportation Plan (RTP), several land-use and transport scenarios were tested on the basis of the Composite Sustainability Index, calculated on the basis of the weighted sum model (Jones *et al.*, 2010). In projects funded by the European commission, SPARTACUS and PROPOLIS, weights are determined by the analytic hierarchy process (AHP) method (Lautso & Toivanen, 1999; Lautso et al., 2004; Spiekermann & Wegener, 2004). Indicators are generated for each individual policy element (e.g., changes in transit fares). Effective policies were combined to evaluate joint impacts, for example, lower transit fares and teleworking could offset some of the negative effects of higher car pricing. As policy combinations are analyzed, additional policy elements are added incrementally, while policies that have a negative or inconsequential impact are eliminated. Recently, May *et al.* (2012) presented a decision-support tool to generate possible policy instrument options. The best performing instruments are found through a scoring system in which the scores are obtained from the professional experts. The scores were initially based on professional judgment and subsequently adjusted by a strategic model, the MARS model. One practical constraint described is the number of combinations possible, i.e., the number of feasible options would be tremendous with the practically considered numbers of the policy instruments, thus the package was limited to a shortlist of the policy instruments. The works described above involve the process of policy level adjustment in a relatively manual way; thus, it may not imply or automatically lead to the development of an optimal policy instrument. Shepherd *et al.*(2006) presented a methodology for the design of optimal transport strategies in which a range of policy instruments are optimised. The objective function is made up of the net present benefits of three sectors: users, providers, and externalities, expressed in the monetary term where the financial constraints were imposed.

This study proposes an approach to determine an optimal coordination of policy instruments in a more general urban policy context where the cost elements are more diversified than a transport policy context. The combination size problem of the possible policy options as addressed by May *et al.* (2012) is properly treated by employing a search algorithm such that the optimization could be more automatic and implies a global solution.

3. POLICY INSTRUMENT SET PROBLEM

In this section, the policy instrument set problem is defined and an example of the problem is presented. Thereafter, computational complexity caused by solving the problem using a thorough search is discussed.

3.1 Definition

The policy instrument set problem is an optimization problem that seeks the best set of policy instruments with PSDM. The constraint conditions are defined in order to keep the level of public services above a certain acceptable level. Public expenditure is calculated by using the objective function. The public expenditure of a certain policy instrument set is calculated on the basis of future distribution that is forecast by urban microsimulations under the enforcement of policy instruments. The optimal solution is a set of policy instruments that satisfies the constraint conditions and minimizes the value of the objective function.

3.2 Example: The elderly residents care service problem

The elderly residents care service problem is taken up as an example of the policy instrument set problem. In this problem, the location subjects are elderly residents who move to the urban center zone according to the policy of the move subsidy. The purpose is the minimization of public expenditure incurred on providing care services to elderly residents. The solution of this problem is a set of two policy instruments $p = \{W, C_m\}$, where W is the allocation of long-term care facilities and C_m is the move subsidy that is given for moving to the urban center zone. The following subsections present propositions, the objective function, and constraint conditions.

3.2.1 Propositions

The elderly residents care service problem is defined with the following propositions:

- N long-term care facilities are allocated in a two-dimensional $X \times Y$ meshed virtual city, shown in Figure 1. $X_c \times Y_c$ zones of $X \times Y$ zones are the urban center zones, while the remaining $(XY - X_cY_c)$ zones are the surrounding zones.
- In the first stage, P_0 elderly residents reside in every zone. According to the policy of the move subsidy, some elderly residents who live in the surrounding zone move to the urban center zone. The higher the value of the move subsidies, the greater the number of elderly residents who move. The probability $R_m(C_m)$ that elderly residents move to the urban center zone under the policy that the residents obtain subsidy of C_m yen by moving is defined in equation (1). Here, α, β, and γ are parameters.

$$R_m(C_m) = \frac{\alpha}{1 + \exp(-\beta \cdot C_m + \gamma)} \tag{1}$$

- The distribution of elderly residents $P(C_m)$ is determined by urban microsimulations. Whether a resident who lives in the surrounding zone will move to the urban center zone is determined by the Monte Carlo method using the move probability $R_m(C_m)$. The zone to which the elderly are to move to is selected randomly from among urban center zones. The number of residents who move is expressed as $P_m(R_m(C_m))$.
- Elderly residents go to the nearest long-term care facility by transfer service. The ratio of receiving the service is R_w (times/person × day). When there are two or more nearest facilities in a zone, all elderly residents in the zone are assigned to each facility equally.
- There are lattice roads that connect each adjoining zone, as shown in Figure 1. It takes T minutes to transfer to the adjoining zone. It takes T/2 minutes to transfer in the same zone. The cost of the transfer service per minute is C_w yen.
- It costs C_b yen to establish a long-term care facility and maintain it for ten years.

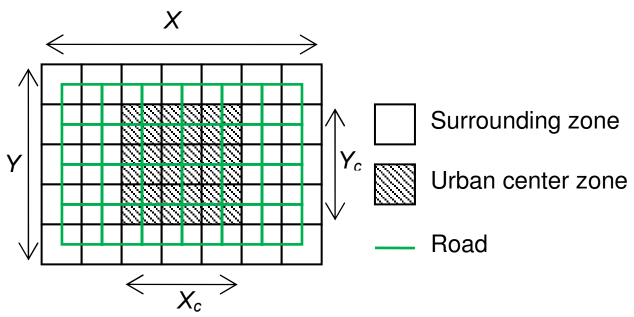


Figure 1 – Two-dimensional virtual city

3.2.2 Objective function

The total cost for subsidizing move $C_M(C_m)$ is calculated using the number of residents who moved $P_m(R_m(C_m))$ using equation (2).

$$C_M(C_m) = C_m \cdot P_m(R_m(C_m)) \tag{2}$$

The time taken to transfer elderly residents in each zone to the nearest facility is determined by facility allocation W. The total cost for providing transfer services for ten years $C_W(W,C_m)$ is calculated using equation (3). Here, $T(W,P(C_m))$ is the sum of the transfer time of all elderly residents.

$$C_W(W, C_m) = T(W, P(C_m)) \cdot C_w \cdot R_w \times 2 \times 365 \times 10 \tag{3}$$

The objective function $E(W,C_m)$ is defined in equation (4). Here, $N(W)$ is the number of facilities to be established.

$$E(W, C_m) = C_M(C_m) + C_W(W, C_m) + C_b \cdot N(W) \tag{4}$$

3.2.3 Constraint conditions

The elderly residents care service problem has the following two constraint conditions:
- The transfer time to a long-term care facility cannot exceed T_{max} minutes.
- The number of elderly residents admitted to a long-term care facility cannot exceed P_{max}.

3.3 Computational complexity

In order to identify an optimal solution for the policy instrument set problem, it is necessary to list all solution candidates, examine whether each solution candidate satisfies the constraint conditions, and calculate the public expenditure. The procedure for solving the elderly residents care service problem naively is illustrated by the flowchart shown in Figure 2. Here, the policy instrument set *PSET* is a direct product of the facility allocation set *WSET* and move subsidy set *CMSET*, and N_{C_m} is the amount of the move subsidy.

$$WSET = \{W_i \mid 1 \le i \le 2^{XY}\} \tag{5}$$

$$CMSET = \{C_{m,i} \mid 1 \le i \le N_{C_m}\} \tag{6}$$

$$\begin{aligned} PSET &= \{p_i \mid 1 \le i \le 2^{XY} N_{C_m}\} \\ &= WSET \times CMSET \end{aligned} \tag{7}$$

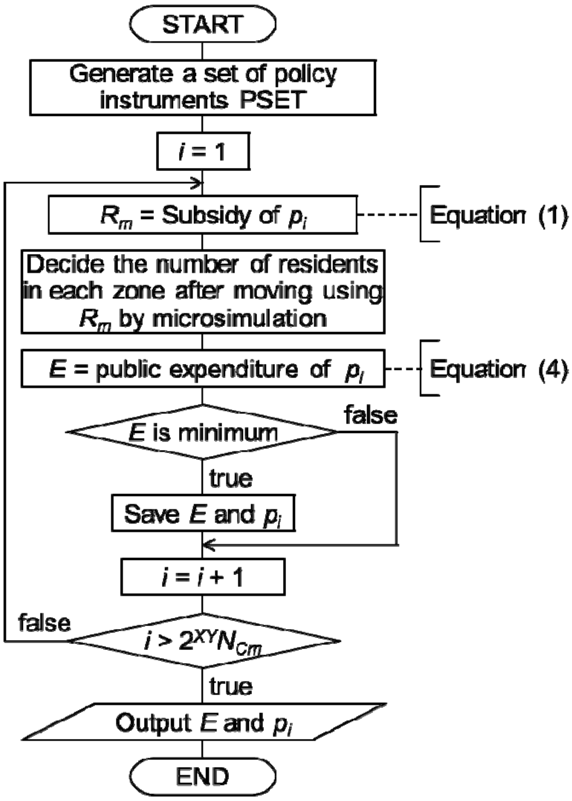


Figure 2 – Flowchart of the naive method

When the move subsidy changes every 5,000 yen from 0 yen to 1 million yen, N_{C_m} equals 21, |*WSET*| equals 2^{XY}, and then the number of combinations of policy instruments becomes 21 × 2^{XY}. For example, the number of combinations is 704,643,072 for X = 5 and Y = 5. Since the calculation of public expenditure requires microsimulation, it takes a certain amount of time to calculate the public expenditure of a set of policy instruments. If application to the actual problem is considered, the naive method is not practical. Then, what is needed is a method that makes it possible to identify the solution within an acceptable time frame.

4. APPROACH FOR SOLVING A SET OF POLICY INSTRUMENTS PROBLEM

In this section, the proposed method for solving a set of policy instruments using the harmony search algorithm is described.

4.1 The harmony search algorithm

The harmony search algorithm is a new technique for solving optimization problems that imitates a musician's improvisation process. Its effectiveness has been demonstrated in various fields (Geem *et al.*, 2005; Otani *et al.*, 2012). Searching for a perfect state of harmony is analogous to solving an optimization problem. When a musician is improvising, he/she plays music through any one of the following three ways.

1) Select any famous piece from his/her memory
2) Adjust the pitch of a known piece slightly
3) Compose an absolutely new piece

In the harmony search algorithm, new candidates are generated using the following three operators. Each operator corresponds to the abovementioned ways of improvisation.

1) Choose one harmony from the harmony memory
2) Adjust a harmony in the harmony memory
3) Generate a new harmony randomly

Here, harmony memory is a set of harmonies. Diversification and intensification are necessary for an optimization algorithm. In the harmony search algorithm, diversification is controlled by the pitch adjustment and randomization operations, and intensification is represented by the harmony memory.

The pseudo code of a harmony search algorithm is presented in Figure 3. G is the maximum number of iterations, R_c is a harmony-memory-considering rate, R_a is a pitch-adjusting rate, and $f(x)$ is an objective function.

```
Initialize the harmony memory;
worst := the worst harmony in the harmony memory;
worstfit := f(worst);
for i := 1 to G {
    r1 := a random number from 0.0 to 1.0;
    if(r1 < Rc) {
        new := a harmony chosen from the harmony memory randomly;
        r2 := a random number from 0.0 to 1.0;
        if(r2 < Ra) {
            new := new adjusted randomly within limits;
        }
    } else {
        new := a harmony generated randomly;
    }
    newfit := f(new);
    if(newfit > worstfit) {
        Replace worst with new;
        worst := the worst harmony in the harmony memory;
        worstfit := f(worst);
    }
}
```

Figure 3 – Pseudo code of a harmony search algorithm

4.2 Design of harmony search for solving the policy instruments set problem

In order to solve the policy instrument set problem using the harmony search algorithm, a set of policy instruments that is a candidate of the problem is expressed as a harmony. For example, a harmony for the elderly residents care service problem is expressed as an array that has $X \times Y + 1$ elements. Figure 4 shows the structure of a harmony. The first $X \times Y$ elements are 0 or 1 and indicate the existence or absence of long-term care facilities. When the element is 1, a long-term care facility exists in the zone; when the element is 0, a long-term care facility does not exist. The last element is a base value used to calculate the move subsidy. When the move subsidy is changed every 50,000 yen from 0 yen to 1 million yen, the element is an integer that is 0 or more and 20 or less.

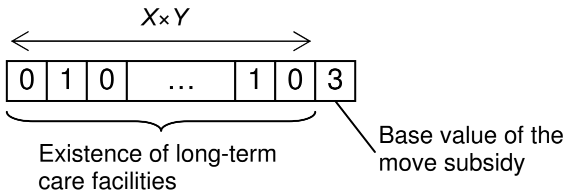


Figure 4 – Structure of a harmony

Each harmony is evaluated by the value of the objective function. The smaller the value, the better is the harmony. The evaluation value for a harmony that does not satisfy the constraint conditions is a rather large value that is effective to eliminate the harmony from the harmony memory. For the elderly residents care service problem, the evaluation value is set to the maximum value in the processor when the transfer time to the long-term care facility exceeds the upper limit or the number of elderly residents admitted to a long-term care facility exceeds the upper limit. The evaluation value for the other cases is calculated using equation (4).

A harmony selected from the harmony memory can be adjusted via the pitch adjustment operation. For the elderly residents care service problem, each element is changed in the following manner.

- For the element that expresses the existence of long-term care facilities, change 0 to 1 or 1 to 0.
- For the element that expresses the base value of the move subsidy, add 1 to the element or subtract 1 from the element.

The procedure for solving the elderly residents care service problem using the harmony search algorithm is illustrated by the flowchart shown in Figure 5.

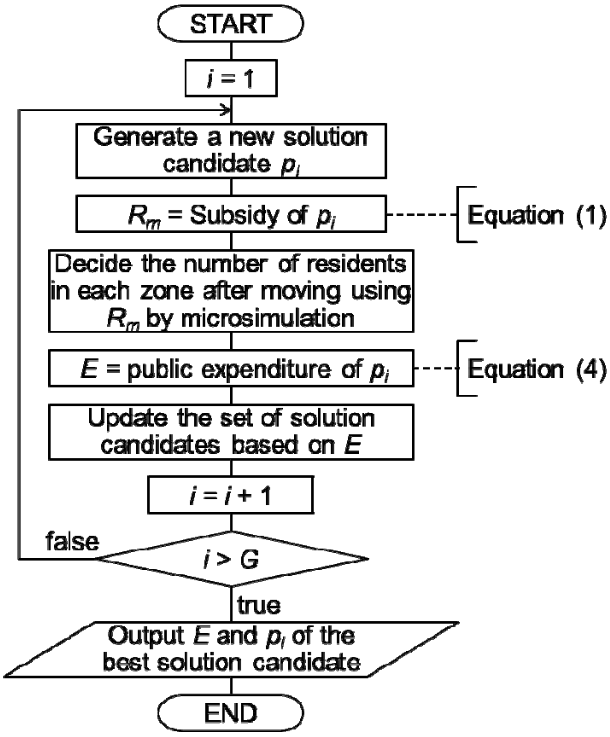


Figure 5 – Flowchart using the harmony search algorithm

5. CASE STUDY

Experiments for the elderly residents care service problem were conducted in order to validate the usefulness of the proposed method.

5.1 Data

The parameters used for the harmony search algorithm in the proposed method are shown in Table 1. The target hypothetical city is a two-dimensional 9 × 9 virtual city that has 3 × 3 urban center zones in the central part. The move subsidy is changed every 50,000 yen from 0 yen to 1 million yen. The parameters used in equation (1) are shown in Table 2. Five kinds of parameter sets prepared for the comparison experiments are shown in Table 3. Parameter set (1) is the basis of comparison. The influence of changing the upper limit of the transfer time T_{max} is examined by the result for parameter sets (2) and (3). The influence of changing the upper limit of the number of elderly residents admitted to a facility P_{max} is examined by the result for parameter sets (4) and (5). The quality of the service to residents of parameter set (2) is higher than that of parameter set (3), and that of parameter set (4) is higher than that of parameter set (5).

Table 1 – Parameters for the Harmony Search Algorithm

Parameter name	Value
Maximum number of iterations, G	200,000,000
Harmony-memory-considering rate, R_c	0.85
Pitch-adjusting rate, R_a	0.35
Size of harmony memory	1,000

Table 2 – Parameters in the Equation of Move Probability

Parameter name	Value
α	100
β	−0.1
γ	5

Table 3 – Parameter Sets for Comparison Experiments

	Number of parameter set				
	(1)	(2)	(3)	(4)	(5)
P_o (people)	20				
R_w	0.1				
T (min)	10				
C_w (yen)	150				
C_b (yen)	300,000,000				
T_{max} (min)	70	50	90	70	70
P_{max} (people)	40	40	40	30	50

5.2 Results

It took approximately 7,500 seconds to solve the problem on a workstation with an Intel Xeon 2.66GHz CPU, 4GB RDIMM. The process of solving the problem for 5 parameter sets was repeated 10 times. The average values of the move subsidy, number of facilities, public expenditure, total move subsidy, total expense for facilities, and total expense for transport services are listed in Table 4. The values of the best solution in each parameter set are listed in Table 5. The higher the quality of services provided to residents, the higher the public expenditure becomes. Further, the higher the quality of services provided to residents, the smaller the number of residents who move.

Figure 6 shows the allocations of the long-term care facilities of the best solution for each parameter set. Zones illustrated in bold lines are the urban center zones. The existence of a long-term care facility is indicated by the shadowed zone. The number in the shadowed zone indicates the number of elderly residents admitted to the facility.

In the case of a smaller upper limit of the transfer time, which indicates parameter set (2), it is necessary to allocate facilities all over the city in order to admit elderly residents in each zone. Accordingly, many residents do not need to move and the total subsidy becomes smaller. However, the transfer distance of each resident increases evenly, and the total expense for transport services becomes higher.

In the case of a small upper limit of the number of residents admitted to a facility, which indicates parameter set (4), the increase in the number of facilities cannot be avoided. Allocating facilities all over the city and equalizing the number of residents in a facility helps to keep the number of facilities down. As with the case of transfer distance, when the total subsidy becomes lower, the total expense for transport services becomes higher. In addition, the expense for establishing and maintaining facilities becomes higher.

In the case of the larger upper limit of the transfer time or the number of residents admitted to a facility, which indicates parameter set (3) or (5), the constraint conditions can be satisfied even if facilities are concentrated in the central part. Accordingly, it is necessary to make many residents move and the total subsidy becomes higher. However, as almost all residents transfer to the central part, the total expense for transport services decreases.

These experimental results show that valid results were obtained within an acceptable time frame using the proposed method.

Table 4 – Average Values of All Solutions

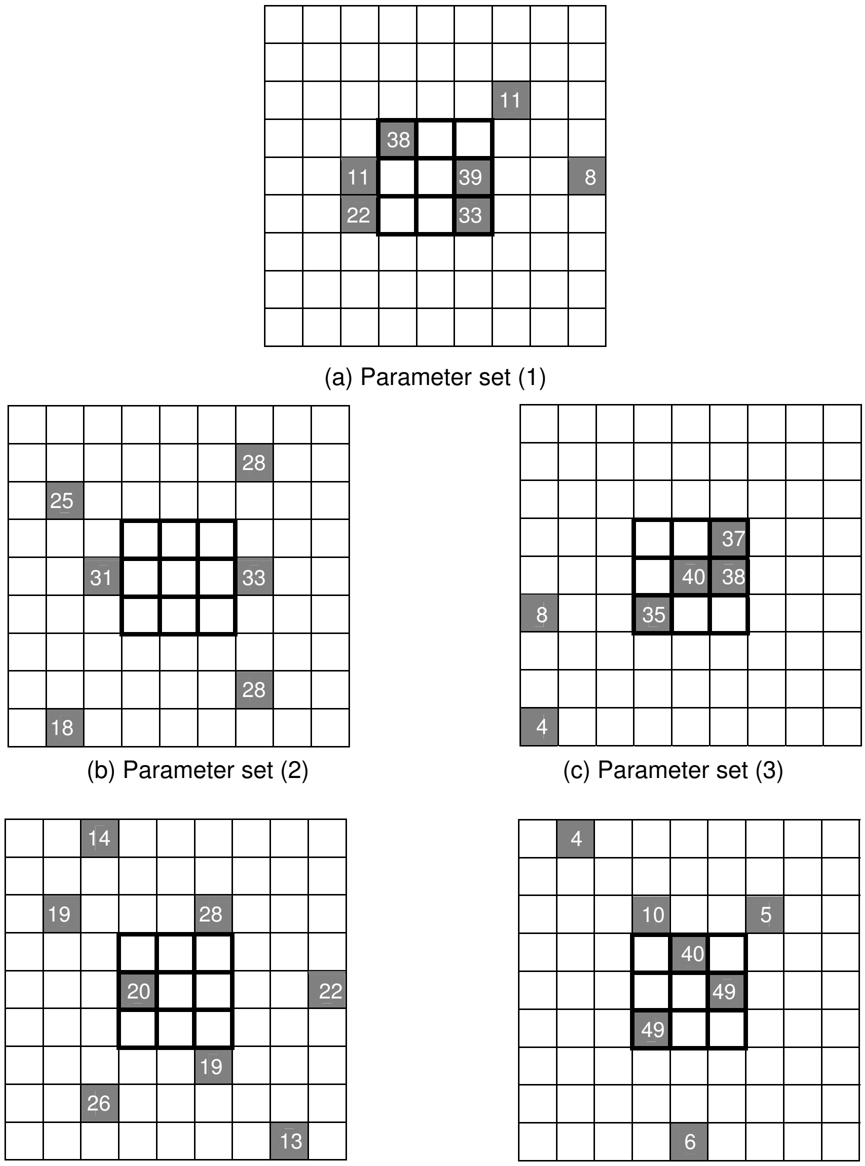
Parameter set	Subsidy for one person	No. of facilities	Public expenditure	Total subsidy	Total expense for facilities	Total expense for transport services
(1)	400	6.9	5,227,230	289,920	2,070,000	2,867,310
(2)	175	6.9	5,276,390	22,290	2,070,000	3,184,100
(3)	290	6.7	5,233,090	166,290	2,010,000	3,056,800
(4)	100	7.9	5,440,080	5,010	2,370,000	3,065,070
(5)	490	6.8	5,106,460	484,620	2,040,000	2,581,850

(thousand yen)

Table 5 – Values of the Best Solution

Parameter set	Subsidy for one person	No. of facilities	Public expenditure	Total subsidy	Total expense for facilities	Total expense for transport services
(1)	550	7	5,077,370	496,100	2,100,000	2,481,270
(2)	250	6	5,158,750	30,500	1,800,000	3,328,250
(3)	600	6	4,973,840	619,200	1,800,000	2,554,640
(4)	50	8	5,354,070	850	2,400,000	2,953,220
(5)	650	7	4,783,010	758,550	2,100,000	1,924,460

(thousand yen)



(a) Parameter set (1)

(b) Parameter set (2)

(c) Parameter set (3)

(d) Parameter set (4)

(e) Parameter set (5)

Figure 6 – Allocations of long-term care facilities

6. CONCLUDING REMARKS

The concept of Transport Demand Management in transport planning indicates that only infrastructure provision will not be effective for solving transport problems. This holds true for other public services as well. Therefore, a more general idea of Public Service Demand Management (PSDM) is introduced in this study. Moreover, the scope of targets for which policy instruments are intended to work is extended to cover land use, transport, and the interaction between the two. The method is developed as a tool to make the approach feasible.

Many land use and/or transport simulation models, either meso or micromodels, have been proposed for urban planning and implementation. However, they have been used only to present future forecasts in the case that a candidate set of policy instruments, proposed by planners, is implemented in metropolises. The original contribution of this study is to use the model for coordinating policy instruments automatically as candidate sets for planners.

Although the case studies in this study are too simple to be directly applied to practical planning and implementation, the results show both the feasibility and usefulness of the method in an actual metropolis. In order to grasp the range of the applicability of the proposed method, further studies must be conducted.

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